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# UK bioenergy innovation priorities: Making expectations credible in state-industry arenas



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## ABSTRACT

The UK government has promoted bioenergy for several policy aims. Future expectations for bioenergy innovation encompass various pathways and their potential benefits. Some pathways have been relatively favoured by specific state-industry arrangements, which serve as 'arenas of expectations'. Through these arrangements, some expectations have been made more credible, thus justifying and directing resource allocation. Conversely, to incentivise private-sector investment, government has sought credibility for its commitment to bioenergy innovation. These dual efforts illustrate the reciprocal character of promise-requirement cycles, whereby promises are turned into requirements for state sponsors as well as for innovators.

Collective expectations have been shaped by close exchanges between state bodies, industry and experts. As promoters build collective expectations, their credibility has been linked with UK economic and environmental aims. When encountering technical difficulties or delays in earlier expectations, pathways and their benefits have been broadened, especially through new arenas—as grounds to allocate considerable state investment. Thus the concept 'arenas of expectations' helps to explain how some pathways gain favour as innovation priorities.

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## 1. Introduction

Over the past decade, UK policy has given renewable energy an increasingly important role as both an environmental and economic imperative. Environmental aims include: reducing greenhouse gas (GHG) emissions, moving to a low-carbon economy and improving waste management. Renewable energy encompasses solar, wind and wave, which convert site-specific sources into electricity.

By contrast, bioenergy has diverse biomass sources and energy outputs. But it largely depends on traditional processes for converting biomass, especially from sources which have been criticised as environmentally unsustainable [1]. To increase bioenergy production, excessive increases in biomass

imports 'could have counterproductive sustainability impacts in the absence of compensating technology developments or identification of additional resources', according to an expert study [2]. Along those lines, the UK government emphasises the need for technoscientific innovation to ensure expansion of 'sustainable bioenergy' [3]. Multiple innovation pathways have competed for public-sector funds, while also anticipating that biomass sources may become scarce, more expensive and/or controversial.

This paper analyses UK innovation policy on bioenergy through the following question: Given various state funding sources, how does each favour different expectations for benefits from bioenergy innovation, thus giving priority to some innovation pathways? Subsidiary questions include: How have future expectations mobilised resources for some innovation pathways more than others? How have some expectations been made more credible through institutional processes evaluating and prioritising them for public funds? In those processes, what have been the arrangements between the public and private sectors, i.e. between

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state and industry bodies? How have arenas and priorities undergone change? To provide answers, we analyse UK priority-setting for bioenergy innovation pathways.

The paper is structured into six sections. [Section 2](#) surveys analytical perspectives on how technological expectations help to mobilise resources, especially through specific arenas. Empirical sections correspond to the different types of comparisons made here. [Section 3](#) analyses how specific UK arenas have favoured some expectations, as a basis for some innovation priorities rather than others. [Sections 4 and 5](#)

analyse how some expectations have been made more credible than before through specific arenas, especially vis a vis previous difficulties for gasification. For algal bioenergy, [Section 6](#) analyses how this overall pathway was made more credible in a specific arena; yet the significant funds were soon lost through a shift in government criteria. Drawing on those various comparisons among pathways and arenas, [Section 7](#) summarises answers to the above questions; [Table 1](#) summarises links between specific arenas, credible expectations and innovation priorities.

**Table 1**

**Arenas of expectations for UK bioenergy innovation.** The four agencies below have given significant funds to bioenergy innovation along different lines. Each column outlines a high-level aggregation through an 'arena of expectations' with distinctive ways to structure relations between selectors and enactors, to involve industry, to fund types or stages of innovation, and to set criteria for success. Funding priorities cannot be explained entirely by technical progress, as indicated in the 'promise-requirement' row.

Arena: selector and/or enactor	Research councils	Bioenergy capital grant scheme	Carbon Trust	Energy Technologies Institute (ETI)
Host/funder Bioenergy-specific unit?	BIS EPSRC Supergen Bioenergy since 2003 BBSRC BSBE since 2009	DTI, then DECC since 2009 Bioenergy-only funding since its establishment in 2002	DTI, then DECC since 2009 Advanced Bioenergy Directed Research Accelerator since 2008	BIS + EPSRC All energy pathways, especially renewable forms, since 2009
Industry role	Industry co-funding or sponsorship, as an indicator of commercial prospects, is an advantage for a proposal in competing for RC funds. Researchers also compete against each other for such support.	Evaluates proposals from organisations, companies, public authorities, etc.	Projects often develop a partnership with industry (but not for algae programme).	Established a club membership, especially of large fossil-fuel companies, which have provided half the funds.
Innovation stages	EPSRC: 'strategic research', i.e. knowledge linking with commercial application. BBSRC: fundamental science underpinning later application	Conventional or novel technologies needing refinement or scale-up	Generally near-market or commercial use (except for Algae Biofuels Challenge programme)	Initial feasibility studies for the entire supply chain, towards upscaling demo projects, thus minimising risk for any single investor
Commercial expectations	R&D results will eventually find commercial application by companies via partnership and/or patent licensing.	5-year grant for energy production will facilitate commercial viability and stimulate demand for energy crops.	Funds will 'overcome technical barriers that are holding back next-generation' bioenergy, e.g. algae and pyrolysis.	Companies together 'identify key areas for strategic investment' via real-world systems, towards making them commercially viable.
Favoured path: example	Advanced biofuels via lab techniques towards facilitating the commercial stage	Minimal competition: numerous diverse proposals funded, sometimes via repeat grants	Algae Biofuels Challenge funding R&D (2008–11 only)	Gasification, esp. for converting bio-waste; and bioenergy-CCS for 'negative emissions'
Expectations of latter example	Advanced (ideally 'drop-in') biofuels lowering net GHG emissions from current transport infrastructure, as well as gaining export markets or intellectual property	Various innovations contributing to targets for renewable energy and GHG savings	Commercially viable algal biofuels by 2020, thus substituting for fossil fuels without demand for freshwater or land	New (or add-on) plants lowering GHG emissions of current infrastructure for fossil-fuel energy, as well as gaining export markets or patents
Promise-requirement cycle	2009 expectations for advanced biofuels by 2020 target were explicitly postponed, yet support was maintained via a promise to bypass the 'fuel vs food' controversy and bring economic benefits.	DECC had weak basis to evaluate promises or to impose requirements for technical progress via the BCGS, which was being phased out by 2013.	DECC criteria changed in 2010, diverging from original promises of the algae programme, leading to its termination in 2011.	Expectations to convert any biomass (especially waste) more efficiently via gasification became more important and credible, despite UK's earlier difficulties ('picking losers').
Contrast with other pathways or arenas	Much less funds were allocated to bio-hydrogen techniques and fuel-storage cells, which face many technical difficulties. Their application would undermine current infrastructure of large incumbent energy companies.	By 2013 the Scheme was deemed an ineffective way to select the best prospects for innovation.	Various public-private partnerships were funding other algal pathways for diverse high-value products, with energy as a by-product.	Policy language has emphasised decentralisation via bioenergy, but such pathways remain marginal in priorities, which favour large-scale centralised plants.

## 2. Analytical perspectives

As theorised by the ‘sociology of expectations’, early-stage technoscientific development needs to mobilise resources on a basis other than evidence of technical progress. This literature survey looks at concepts for analysing such expectations—their basis, role, credibility and arenas.

### 2.1. Expectations as potential requirements

Expected future benefits have been theorised as ‘real-time representations of future technological situations and capabilities’ [4]. Rather than simply predict or describe future realities, moreover, future expectations ‘guide activities, provide structure and legitimation, attract interest and foster investment. They give definition of roles, clarify duties, offer some shared shape of what to expect and how to prepare for opportunities and risks’. Expectations play a central role in mobilising resources, ‘for example in national policy through regulation and research patronage’ [5]. Technological expectations can help to convince funders and other practitioners to support a development. Technology innovators may exaggerate their promises for several aims—‘in order to attract attention from (financial) sponsors, to stimulate agenda-setting processes (both technical and political) and to build ‘protected spaces’ [6].

Each pathway may undergo a hype cycle, which has been theorised as a ‘promise-requirement cycle’. Technological expectations can turn into requirements for the actors who formulate them. Promises create tensions—attracting resources and protection, but also returning as obligations. Through ‘promise-requirement cycles’, a techno-optimistic claim or a promise may become a required action—e.g. a technical specification to be fulfilled and/or political support to be provided [7]. Through technoscientific development activities, outcomes are assessed; new promises and requirements become more specific. This cycle may be repeated several times [8].

Innovators may be required to demonstrate technical progress warranting further investment. Given the need to exaggerate expectations, ‘the frequent disappointments to which they lead are accompanied by serious costs in terms of reputations, misallocated resources and investment’ [9].

Different pathways compete for resources according to expectations for their future performance, though they can also be mutually reinforcing. In a case study of hydrogen fuel storage, promoters sought to enhance the credibility and visibility of their claims through ‘interdependencies of expectations at various levels: the credibility of the generic expectation of hydrogen as an energy carrier is built upon the functional and specific expectations of the constituent elements of the chain, while these, in their turn, refer to the encompassing vision’ [10]. These interdependent expectations can become a double bind, [11] though they can also provide more flexible opportunities.

The authors generalise as follows: such competitions among imagined future solutions ‘result from R&D, political struggles, activism of non-governmental organisations and, occasionally, demonstration projects’ [12]. Likewise the converse: together those dynamics can influence R&D priorities. Specific expectations can be socialised. For example, ‘technologies presented as

the next generation... are self-justifying because the notion of next generation is widely accepted’ [13]. As this illustrates, when widely shared, expectations can become ‘part of a generalised and taken-for-granted social repertoire’; they become a ‘depersonalized social construction’, not attributable to specific individuals or groups of actors. Whenever they become societal assumptions or ‘collective’, such expectations can even guide or justify the actions of those who do not necessarily share them [14].

When promoting technological pathways, actors’ roles have been distinguished as follows: actors that create technology are *enactors*, while actors that select technology are *selectors*. Technology selectors have to balance several contradictory criteria, whose balance can shift over time; ‘the fate of enactors is much more related to the success of one or more technologies, while selectors can afford to be much more indifferent to the fate of a particular technology’. The distinction between those categories is not ontological, since the same actor can play either role in different contexts [15]. Generalising from their case study, the authors argue that key individuals act as technology selectors towards technology innovators and then ‘emphatically act as technology enactors towards their [organisational] leadership’ [16]. Thus the same actor may select and promote specific technological expectations.

### 2.2. Arenas of expectations

In the academic literature on technological expectations, case studies have generally focused on actors within a specific context, while taking this for granted. There is a theoretical gap regarding how a specific context favours some types of expectations more than others, especially where multiple options compete for support. This gap has been somewhat filled through the ‘arena’ concept.

When competing with each other, technology enactors seek to mobilise resources via a collective social process in ‘arenas of expectations’ (see Fig. 1). Here technology selectors need to be repeatedly convinced of the technology’s future potential:

These arenas can be defined as the loci where expectations are voiced by the enactors and tested by the selectors, where they are confronted with experience, knowledge, and interests... These multi-actor interactions take place at scientific conferences and journals, in the wider media, committees, research councils, and so forth [17].

From their case study, the authors further argue that some future expectations became more credible by portraying a specific technoscientific pathway as feasible, e.g. as a readily available solution. In their case study, credibility depended on



Fig. 1. Arenas of expectations (n17, p. 160).

'identification and construction of a path forward and a target performance level that the technological option is supposedly able to meet'. Proponents emphasised 'performance measures that are most favourable to their solution and less so for their competitors'. They promoted hydrogen as 'not only an option with great potential for the long term, but also something that is very much happening today', e.g. in niche markets such as forklifts and in test programmes with fleets of hydrogen vehicles [18].

As the authors note, each overall trajectory has multiple options.

It is not fully understood why some options are thought to be credible and others are not... This is especially problematic in those cases in which multiple technological options compete for selection. In such cases, the enactors need to position their option in relation to other options, and selectors need to select those options that they deem most viable... The arenas of expectations are then the linchpins between those actors that enact their technological options and those actors that select the most promising options. In the arenas of expectations, claims about future technological options are launched, compared, elaborated and assessed [19].

Credible expectations can be analysed with the concept of 'arenas', especially given that 'multiple arenas may co-exist at various levels of aggregation. Highly detailed expectations of materials or techniques are tested in different arenas than, say, expectations about the hydrogen energy system as a whole' [20]. The distinction among 'various levels' will be extended here – to different sub-categories of a general pathway, to different innovation stages, and to different relations between public and private sectors – in our study of UK bioenergy innovation.

As a metaphor in political science, the concept of 'arena' describes the symbolic location of political actions which influence collective decisions and policies. Arenas are neither geographical places nor organisational systems; rather, they describe all actors' actions and interrelations around a policy issue. Examples of such arenas include elections, markets and regulatory procedures [21]. Conceptualising distinctive issue-arenas has helped to explain why some actors and arguments more readily gain influence there; each arena is more favourable to some issues and framings than others [22]. By analogy, state bodies sponsor diverse arenas where technology enactors may promote expectations and seek resources for specific innovation pathways.

In the general UK context, innovation policy has had a strong commitment to the biosciences (aka Life Sciences) since the 1990s. According to a critical analysis, this commitment has rested on deep assumptions, in particular: that the relevant UK science base is internationally strong, that this base powers industrial success, in turn ensuring that the research will be applicable in the UK; that the underlying science has cross-over potential among industrial sectors; and that public expenditure is justified by the potential for UK economic growth. Contrary to policy assumptions, there is weak evidence of a domestic linkage between R&D and industrial success, especially given the global character of both [23]. Indeed, global ambitions have been conceptualised as 'diplomacy for

science', which 'seeks to facilitate international cooperation, whether in pursuit of top-down strategic priorities for research or bottom-up collaboration between individual scientists and researchers' [24].

In that wider policy context, UK research councils have set and justified their priorities as 'strategic research', i.e. a strategic response to current and future societal challenges. The energy area exemplifies such engagement with agenda-setting for research policy, according to an academic study [25]. From the EPSRC standpoint, 'Our research portfolio will be focused on the strategic needs of the nation, such as green technologies and high-value manufacturing, and will retain the capability to tackle future challenges and capitalise on new opportunities' [26].

Drawing on the above perspectives, let us examine UK bioenergy innovation. Its specific pathways and budgets have proliferated during the past decade, in ways which can be mutually reinforcing for 'bioenergy' as a high-level aggregation. Rather than analyse a competition for funds, this paper mainly compares various arenas through the overall question: How does each arena favour different expectations for benefits from bioenergy innovation, thus giving priority to some innovation pathways?

### 3. Research methods

In this paper, technological expectations relate to a detailed study of state bodies' policies, as briefly described here. A decade ago bioenergy was being promoted mainly by two government bodies—the Dept of Trade & Industry (DTI) and Dept of the Environment, Farming and Rural Affairs (DEFRA). Since 2009 the new Department of Energy and Climate Change (DECC) has led bioenergy policy, shared with DEFRA and DfT, the latter especially for liquid biofuels. Meanwhile the DTI was renamed the Dept for Business and Industry (BIS). These changes imply an increased plurality of state bodies and policies promoting different expectations.

Public-sector funds for novel bioenergy technology have several sources. 'Strategic research' has been funded mainly through Research Councils—in particular, the Biotechnology and Biological Sciences Research Council (BBSRC), and the Engineering and Physical Sciences Research Council (EPSRC). The latter has co-funded the Energy Technologies Institute (ETI), self-described as 'a UK-based private company formed from global industries and the UK Government'. Near-market innovation has been funded mainly through government departments, e.g. via specific project grants or subsidy for renewable energy. The study underpinning this paper used two main methods of data gathering: policy documents and semi-structured interviews.

Document analysis focused on expectations for economic benefits and environmental sustainability. Initial results led to a more systematic search of documents over the past decade, in order to identify discursive patterns—among relevant bodies and over time.

Specifically, the study analysed more than thirty documents from several bodies—especially government departments, research councils, research institutes, parliamentary hearings, industry and NGOs. As listed in the References section, sources include: government departments (e.g. DEFRA, DTI, DECC), expert reports that they have cited and generally funded (e.g. AEA, NNFC, E4tech, ERP, LCICG), research councils



(e.g. BBSRC/BSBEC, EPSRC with ETI), other state bodies (EAC, RFA, CCC, etc.) whose views elicit government responses, and industry organisations (e.g., REA). We investigated how difficulties in technological progress were accommodated or bypassed through expectations for economic and sustainability benefits.

The document analysis provided a stronger basis for semi-structured interview questions, which investigated in depth the policy process of selecting priorities for bioenergy R&D. Face-to-face interviews have been carried out with 20 individuals from the same bodies which originated the policy documents (listed above and in the References section). The interviews lasted 30–90 min, with mean duration of 70 min. A topic guide incorporated key theoretical categories of imaginaries. The topics were as follows: key national research priorities for sustainable bioenergy; the role of specific policy organisation; the priority-setting processes; accounts of sustainability; future societal vision for bioenergy.

#### 4. UK bioenergy innovation: shifts in arenas and priorities

In the UK decarbonisation efforts are stimulated by mandatory targets under the Renewable Energy Directive [27]. EU member states must obtain 10% of their transport fuel from renewable sources; biofuels have been expected to provide most. The UK must also obtain 15% of all its energy from renewable sources by 2020; it seeks to fulfil at least half that target through bioenergy—a great expansion from only 2% in 2011 [28]. The UK has more ambitious longer-term targets: the Climate Change Act 2008 mandates GHG reductions of at least 34% by 2020 and 80% by 2050.

Environmental and economic aims are combined in government policy. Through measures such as renewable energy, Britain must ‘make the necessary transition to low carbon—right for climate change, energy security and jobs’ [29]. According to the relevant Minister, ‘the promise of the low-carbon economy is breathtaking. In jobs, in goods and services, and in finance, green opportunities are not just emerging. They are blossoming’ [30].

In particular, bioenergy policy seeks national economic benefit of two main kinds—lowering national costs of GHG savings, and creating or capturing economic wealth [31]. The latter can mean profit, jobs, licence patents, royalties, etc.—according to the Technology Strategy Board (interview, TSB, 15.06.12). Governed mainly by industry representatives, the TSB has identified genomics as crucial means towards novel microorganisms, enzymes and crops which can provide more sustainable bioenergy [32]. Commercial benefits can be achieved in various ways, e.g. via technology-licensing revenue through a plant being built somewhere else in the world, or revenue from constructing a plant in the UK, according to a government consultant (interview, E4tech, 19.06.12).

Bioenergy features diverse biomass sources and conversion techniques for various products. This diversity makes bioenergy more complex than other forms of renewable energy. Since promoting bioenergy at least a decade ago, the UK government has not stated any specific priorities for technoscientific innovation. No such priorities can be identified by long-time insiders (interview, Carbon Trust, 03.11.11; interview, E4tech, 19.06.12).

For renewable energy in general, UK policy has implied that innovation pathways are constrained or even chosen by external forces, thereby leaving priorities ambiguous. Various measures are meant to ‘deliver’ government targets, while variously attributing responsibility to innovation, technologies, commercial development or the market [33]. Along similar lines, ‘The government does not pick winners; industry is better at it’, say senior civil servants (DECC participant, bioenergy workshop, 13.10.11; also interview, DECC, 14.08.12).

While this view is widely shared by industry, it has regarded support measures as inadequate, even for market-ready technologies such as Combined Heat & Power:

If you [the government] specify that you seek to achieve a particular trajectory and it is credible, then back it up with policy that is investable, once you have got those three things together, then developers might go ahead... But if you say ‘We want to decarbonise energy use by 2050’ and then you say ‘We will leave it entirely up to the market for that to happen’, there is a lack of detail for it to be credible. We know that the market will not do it without government intervention (interview, CHPA, 19.06.12).

Despite the government’s ambiguous language, funding arrangements do influence innovation priorities. To fulfil mandatory targets, ‘We are not backing winners in that respect, but we do have an interest in steering to some extent’ (interview, DEFRA, 03.11.11). Multiple policy aims offer many opportunities to raise expectations and investment for several technoscientific pathways. These have undergone ‘hype cycles’:

High versus low expectations is a continual process that happens in bioenergy. That is, new products come along, a hype cycle starts, and everyone says that it’s great. Then you get into more detail of doing it and you find that there are always issues if you didn’t look at it carefully enough before you started the hype (interview, E4tech, 03.08.12).

The rest of this section looks at priorities at two broad stages: early-stage ‘strategic research’ and middle-stage scale-up or demonstration projects.

##### 4.1. ‘Strategic research’

Early-stage bioenergy research has been funded mainly through research councils. In particular, the Engineering and Physical Sciences Research Council (EPSRC) set up the Supergen Biomass and Bioenergy Consortium in 2003. The Biotechnology and Biological Sciences Research Council (BBSRC) set up the Sustainable Bioenergy Centre (BSBEC) in 2010.

Illustrating the wider drive for strategic research, global economic expectations have informed bioenergy R&D priorities. Scientists’ proposals advocate specific technoscientific pathways as means to fulfil various policy aims and to anticipate economic gains attracting private-sector sponsors. Their financial contribution has been an advantage or even a condition for a proposal to gain a Research Council grant.

Co-funding has come from global companies in the biotech, enzyme, sugar and energy sectors [34]. Such industrial interests inform priorities for strategic research.

Resulting from those arrangements, bioenergy research priorities have favoured specific trajectories, especially techniques for converting lignocellulosic biomass into advanced biofuels (also called next-generation, second-generation, etc.). This priority gained further impetus from controversy over mandatory biofuel targets increasing demand for food biomass and causing environmental harm. To justify the targets, a sustainable solution was foreseen in advanced biofuels converting non-food biomass.

Proponents have emphasised at least three future benefits justifying policy support and industry finance. First, the oil and vehicle industries seek to recoup their past infrastructural investment. According to the Director of a Research Council, for example, 'Sustainable biofuel... is one of the few alternative transport fuels that we could roll out quickly using current infrastructure' [35]. Expert reports recommend R&D support for future 'drop-in' biofuels, i.e. direct functional substitutes for petrol [36]. Second, future biofuels will provide opportunities for UK competitive advantage in marketing its technoscientific skills and in licensing technology: 'the UK could potentially capture 5–10% of the global market within select niches of bioenergy', e.g. by exporting intellectual property for advanced biofuels, according to a report from DECC's Low Carbon Innovation Co-ordination Group [37]. Third, to fulfil EU targets for renewable energy in transport fuel, all member states must greatly expand biofuel use—preferably 'advanced biofuels' by the 2020 deadline. Despite that aim, such fuels will not be ready in time, as the UK government quietly acknowledged in 2010 [38].

Nevertheless wider economic aims drive biofuel R&D. If technically successful, lignocellulosic butanol would be a better functional substitute for petrol, as well as offering the UK a competitive advantage for partnerships between academic institutions and companies. In a biorefinery perspective, moreover, the R&D provides a platform for high-value products, which are deemed necessary in order for advanced biofuels to become economically viable. 'Further understanding the potential of co-products for these conversion routes could lead to high-value biochemicals which could have a significant effect on overall plant economics', according to the above DECC-sponsored report [39].

Thus biofuel research opens up wider agendas for public-sector scientists and companies, together seeking patents on novel processes. According to a scientist who carries out such research under contract from a petrochemical company:

Chemical companies think: 'we will have to solve these problems as well...' So the research going into biofuels will have a spin-off into useful chemicals... Government imperatives for fuel and the commercial need for replacement chemicals are a happy synergy (interview, BSBE, 06.07.11).

Resonating with the BBSRC's visions of a bioeconomy, [40] such expectations help to explain why R&D priorities favour next-generation biofuels and higher-value, low-volume products.

#### 4.2. Scale-up: beyond the 'valley of death'?

Looking beyond R&D, a key aim has been to overcome the 'valley of death' which has generally kept UK research distant from commercial application, especially in bioenergy [41]. According to a research manager:

In the UK we can produce very good science. But you've got to put up quite a lot of money and expend quite a lot of effort to convert that science into a commercial application. If you've got it to the other side of the valley of death, then people pick it up with open arms (interview, BBSRC, 05.04.11).

According to a large energy company:

For the banks and other larger-scale investors, it would be far too risky to invest in an early-stage company. At that point, we were asking 'What do you think the problem is?', and they all say it's the scale of the investment because bioenergy plants are capital intensive. So that's really the main challenge (interview, BP, 03.08.12).

To overcome the obstacle, a possible solution was the Bioenergy Capital Grants Scheme, meant to provide 'market pull' by subsidising energy production [42]. It funded 'conventional technology plant' as well as novel technologies [43]. It sought to give an opportunity to various trajectories, often by renewing grants over a decade (interview, DECC, 14.08.12).

The scheme provided numerous grants for up to 5 year duration, with some successes. But the terms often were too difficult, even for some near-market technologies such as CHP. According to an industry lobby:

The government will give you a five-year window in which to build your project; if your project comes on line late, it will be penalised. Now, that makes sense from a government policy perspective... But no power station is ever commissioned on time; they are always late because they are quite complicated things. So the risk associated with penalties is too big, and investors just walk away (interview, CHPA, 19.06.12).

Greater difficulties arose for technologies more distant from commercial readiness. Despite several years' funding, some did not reach the stage of working technically or attracting private-sector investment.

When you talk to developers, the answer is always that we are 2–3 years away, or 10 years away. And if you talk to them 5–10 years later, it's always the same story: we are 3 years away, or we are 10 years away. So you get stuck: you are paying very large support levels, but you are not getting the energy generation. You may not be notably moving down the innovation pathway. Then as a government you have got a tough decision to say: right, this isn't working, so perhaps we should be concentrating elsewhere... And 4–5 years normally isn't enough for R&D, not even enough to build a biomass combustion plant—certainly not from the standpoint of winning your

grant, then planning it, installing it etc. (interview, DECC, 14.08.12).

The numerous difficulties were eventually diagnosed as a systemic problem of the funding arrangement. By 2012 DECC judged that the Scheme was an inappropriate way to fund R&D. Rather than a Ministry alone judging prospects for future success, this role was broadened to industry through other arrangements.

In 2009 the Energy Technologies Institute (ETI) was set up as 'a UK-based private company formed from global industries and the UK government', with an initial investment fund of £1 bn. Industrial members include major energy, oil and vehicle multinationals (e.g. EDF, E.ON, Shell, BP, Rolls Royce, etc.). ETI's Energy System Modelling Environment (ESME) helps 'to identify key areas for strategic investment', especially for bringing together all components necessary for real-world systems, not simply technologies.

As contributors to ETI, industry members have a say into what we do and how we do it. But each industry member only has 1 vote in 12, so they cannot railroad certain activities. The government is the biggest member but has only 50% of the clout (interview, ETI, 08.06.12).

For near-commercial scale-up, ETI reaches agreement among several companies which thereby share the high costs and privately appropriate the economic benefits, especially through patents:

For the middle stage we have the Energy Technologies Institute, a partnership where government invests a certain amount. We have multinational companies who join and invest significantly more. And only partners within ETI get the benefits. So it encourages multinationals to put significant amounts of money in a pot because they feel it's offering them a sustainable competitive advantage. Whereas normally when governments invest in research studies, we encourage that work to be shared as widely as possible (interview, DECC, 14.08.12).

From industry's standpoint, the arrangement helps to minimise longer-term financial risks:

The UK has little appetite to take the financial risk; hence ETI was set up as a Club. De-risking technology means identifying technological needs in the longer term, as a basis for pooling company funds and thus reducing the financial exposure of any one company, with 50% of the funds from government (interview, ETI, 08.06.12).

For the bioenergy area, ETI's industrial contributions feature fossil-fuel companies, and at least two bioenergy programme managers have come from BP. In parallel with ETI's activities, the feasibility and benefits of various bioenergy pathways were being evaluated by DECC's Low Carbon Innovation Co-ordination Group. Its report evaluated technoscientific readiness, prospects and needs for various conversion processes. The group's membership includes ETI and the Technology Strategy Board, which is governed mainly by industry representatives. The evaluation also drew on ETI's ESME exercises. As another important contribution, ETI's Strategic Advisory Group includes

the Director of the National Non-Food Crops Centre (NNFFC), a hybrid organisation combining expert advice to government with a private consultancy role. Its expert reports have resonated with ETI's priorities, e.g. on gasification [44].

In this overall state-industry arena, some future expectations have been made more credible. These informed ETI's decisions to invest in major demonstration projects, especially for gasification and bioenergy-CCS, as described next in turn.

## 5. Gasification: flexibly converting biowaste

Gasification uses high temperatures to convert biomass into syngas, which can be further converted into various energy forms. With a long history, especially in converting coal to liquid fuel, gasification has recently attracted greater interest as a flexible means to convert various wastes. Gasification has undergone much technoscientific development abroad but only sporadically in the UK, at least until recently.

In the late 1990s state support was directed at new technologies, especially gasification and pyrolysis, with expectations for short-term commercial scale-up. In particular the ARBRE (Arable Biomass Renewable Energy) demonstration project was an integrated gasification-combined cycle system to generate electricity from dedicated energy crops. Its two funding sources had contradictory aims. A 15-year contract from the Dept of Trade & Industry (DTI), under the Non-Fossil Fuel Obligation (NFFO), was intended to support reliable, ready technologies. In parallel, EC funds aimed to support experimental technologies [45]. Such scale-up efforts for experimental technologies were premature, according to an academic study:

The targeting of more advanced or novel technologies was even a greater failure as the most advanced technologies have failed to materialise. This focus on novel technologies has come at the expense of support to more mature technologies which would have helped the biomass energy sector to grow and expand [46].

In those ways, high expectations mobilised resources but resulted in a double failure—gaining little technical progress, and even damaging the government's reputation. By default, energy supply companies had to import other conversion technologies which were ready for commercial use—the reverse of the original aim. Consequently, the government has been criticised for 'picking losers'.

More recently, future expectations for gasification again have been raised by government and expert reports. What role for UK investment and expertise? According to a 2009 expert report, gasification will be developed first abroad. So a key aim is to develop UK technoscientific skills which have broader economic relevance. According to a report published by the National Non-Food Crops Centre, a hybrid organisation combining expert advice to government with a private consultancy role:

The gasification and pyrolysis pilots would provide general project development related skills that might be applicable to biomass to liquids, and bring to bear UK strengths in engineering and petro-chemicals... 'there may be economic



opportunities to be gained from the UK developing a more strategic position in the sector and investing in supporting the development of technologies and skills in pilot or demonstration activities' [47].

Whenever gasification becomes more efficient and flexible, the technology is expected to provide input-substitutes for oil. R&D priorities favour gasification as a flexible way to fuel current transport infrastructure; it can generate 'drop in' solutions particularly in the difficult sectors of aviation and heavy goods vehicles. For both sectors, the government has indicated that biofuels should be prioritised because 'no other solution is available', according to the NNFFC Director [48].

In those ways, gasification has been expected to convert various wastes into novel biofuels, as well as create substantial employment. According to later study by the National Non-Food Crops Centre, the technology could generate substantial transport fuel, even from household rubbish, while also generating much employment:

Under favourable economic conditions and strong improvements in policy support, projections suggest advanced biofuels could meet up to 4.3% of the UK's renewable transport fuel target by 2020.... At this scale advanced biofuels would save the UK 3.2 million tonnes of CO<sub>2</sub> each year – equivalent to taking nearly a million cars off the road – and create 6000 full-time construction jobs and over 2000 permanent jobs supplying and operating the plants [49].

Drafted during 2010–12, a report from DECC's Low Carbon Innovation Co-ordination Group emphasised future benefits 'from select conversion technologies which are capable of converting wastes and other sustainable feedstocks'. Other countries were developing gasification but were not expected to focus on biomethane production. Earlier-stage conversion has the highest potential for reducing the cost of GHG savings. Technoscientific advances would improve the conversion efficiency of gasification, thus eventually making its energy cheaper than from combustion. 'Proof of concept at scale is the primary innovation need for these technologies, which could realise much of their cost reduction potential over the next decade', [50] thus anticipating public benefits sooner rather than later.

Citing the LCICG report, *UK Bioenergy Strategy* highlighted gasification as one of three long-term 'hedging options' to deal with various future uncertainties. Foreseen benefits feature a flexible means to convert various feedstocks, e.g. carbon-based waste such as paper, petroleum-based wastes like plastics, and organic materials such as food scraps. Such conversion could offer environmental advantages over waste incineration, as regards waste disposal and energy yield [51].

To move forward gasification, the Energy Technologies Institute invested in a demonstrator project, justified partly as a contribution to 2050 targets:

The ETI has announced it is seeking partners for a new £13 million project to help design and build a next-generation energy-from-waste demonstrator plant to convert typical wastes into electricity and heat. The ETI is focused on the acceleration of the development of affordable, clean and secure technologies that will help

the UK meet its legally binding 2050 climate change targets... [52].

This investment anticipates a UK competitive advantage in waste-gasification technology (interview, ETI, 08.06.12).

As another benefit, gasification is also expected to make biowaste-CHP more economically viable: 'Gasification systems can also be used for small-scale heat and CHP applications, which are commercially deployed with support in some countries' [53]. Biowaste is spatially distributed, thus offering opportunities for decentralisation. In this basis, UK policy has long advocated biowaste-CHP as a means to decentralise production, while also enhancing use of waste heat, thus saving GHG emissions [54].

An extra aim is to enhance compatibility with carbon capture & storage (CCS). As a major difficulty, BioSNG systems have 'a poor compatibility with CCS systems', as a reason for the little global investment in gasification [55]. This obstacle was turned into a challenge: gasification 'also enables carbon capture & storage, which is becoming a major topic across Europe as it delivers negative GHG emissions' (interview, ETI, 08.06.12; see also next section).

In all those ways, gasification has been newly funded through expectations for multiple economic and environmental benefits, as elaborated by expert studies. Such expectations have been made more credible through new arenas linking UK policy aims with industry interests.

## 6. Bioenergy-CCS: mitigating high-carbon systems

Carbon Capture and Storage (CCS) has been globally under development mainly for gas and coal-fired plants, with potential adaptation to bioenergy such as co-firing. CCS has a central role in the government's *Carbon Plan* to fulfil 2050 targets for GHG reductions. Among three future scenarios, one greatly expands bioenergy, which could be made carbon-negative through a link with CCS:

Future 'Higher CCS, more bioenergy' assumes the successful deployment of CCS technology at commercial scale and its use in power generation and industry, supported by significant natural gas imports, driven by changes such as a reduction in fossil fuel prices as a result of large-scale exploitation of shale gas reserves. It also assumes low and plentiful sustainable bioenergy resources processes [56].

More recently, UK expert reports emphasise the carbon-saving benefits of using CCS in conjunction with biomass [57]. 'When applied to biomass firing, CCS can reduce emissions even further, potentially as a source of relatively low-cost negative emissions' [58]. This could cheapen GHG savings when co-firing biomass with fossil fuels.

The *UK Bioenergy Strategy* emphasises adaptation of CCS to biomass feedstock:

Bioenergy carbon capture and storage (BE-CCS) could produce bioenergy in the form of biopower, biohydrogen, bioheat and biofuels, but most significantly permanently stream underground the waste carbon from these processes that was taken from the atmosphere by plant

growth, providing net carbon removal from the atmosphere or 'negative emissions' [59].

A biohydrogen alternative is envisaged for the period after 2030, when 'the priority should be for continued use of biomass resource in process heating, and in the transport sector, either through bioenergy hydrogen production with CCS or through biofuels for aviation and shipping if CCS is not available' [60].

As the *Strategy* emphasises, a CCS Roadmap had already outlined steps being taken to achieve cost-competitive CCS. However, 'The relative costs and availability of the technologies are subject to significant uncertainty, especially for unproven technologies in later periods, e.g. biohydrogen for transport' [61]. Given these uncertainties about cost and feasibility, BE-CCS lies beyond the three 'hedging options' (interview, DECC, 14.08.12). According to some critics of BE-CCS, its promise to provide carbon-negative emissions depends upon numerous optimistic assumptions—about biomass production, biomass combustion, carbon capture, etc. [62].

To clarify ways forward, ETI allocated £0.5 m to a project evaluating 'Biomass to Power with CCS', with a consortium including academic and industrial partners. This study 'identified a specific opportunity to develop capture technology for new-build, pre-combustion coal capture based on physical separation of CO<sub>2</sub> from synthesis gas', i.e. initially in coal plants. It invited company proposals 'for full-scale demonstration by 2015 and adoption into full scale commercial power applications by 2020' [63].

CCS design faces infrastructural choices. The diffuse location of biomass offers opportunities for decentralised systems. According to an EPSRC Supergen study, biomass feedstock within a localised design would enhance GHG savings:

While biomass co-firing with coal offers an early route to BE-CCS, a quite substantial (>20%) biomass component may be necessary to achieve negative emissions in a co-fired CCS system. Smaller-scale BE-CCS, through co-location of dedicated or co-combusted biomass on fossil CCS CO<sub>2</sub> transport pipeline routes, is easier to envisage and would be potentially less problematic [64].

Nevertheless UK state bodies assume that BE-CCS will and should complement centralised infrastructure: biomass is foreseen as supplying a few large-scale centralised coal or gas plants (interview, ETI, 08.06.12).

As another expectation, moreover, CCS is sought for negative emissions that lighten the burden of GHG savings from fossil fuels: 'These negative emissions could then be used to offset fossil fuel emissions from other harder-to-decarbonise sectors' [65]. Put more explicitly: 'Negative carbon emissions could lower the cost of a low-carbon energy supply because we could go on using gas, possibly even using coal, and balance it out with CCS' (interview, DECC, 14.08.12; cf. ETI comment at bioenergy workshop, 20.11.12). Thus optimistic expectations for BE-CCS complement longer-term dependence on fossil fuel.

Several potential projects have encountered difficulties before they would have begun. For CCS installation planned at Longannet coal-fired plant in 2011, industrial partners disagreed over the necessary state funding. CCS generally has

faced many obstacles to investment. Companies see it as an end-of-pipe cost, e.g. as an environmental burden necessary to justify fossil energy, rather than as an economic benefit.

## 7. Algae conversion: shifting expectations and arenas

While previous sections have analysed how some expectations and thus priorities became favoured within a specific arena, the final case focuses on a high-level aggregation, algal technology, and how this became differentiated across arenas. Algal biofuels gained credible expectations for several benefits, as a basis for substantial state funds through the Carbon Trust priorities; but DECC soon changed its criteria and abandoned the entire programme. By contrast, more specific algal pathways gained funds via various public–private partnerships. These outcomes illustrate diverse links between arenas, expectations and their credibility, especially at lower-level aggregations.

### 7.1. Expectations for algal bioenergy

Algal biomass sources have been expected to avoid any conflicts over arable land, thus avoiding the 'food versus fuel' controversy, while also generating diverse valuable products. These interdependent expectations have made overall credibility dependent on multiple pathways, while also offering flexibility in shifting expectations to bypass obstacles.

Future expectations and obstacles have been elaborated in various expert reports. As a special advantage for the UK, algal technology could build on national strengths: 'in the areas of fundamental plant science, micro and macro-algae, fermentation, pyrolysis, we also have industrial capacity for some thermo-chemical routes and bio-chemical routes' [66]. For producing aviation fuel, algal feedstock could offer much greater GHG savings than oilseeds. However, 'These routes are unlikely to be commercial before algae can be cultivated economically at a large scale'. For algal systems to become economically viable, moreover, higher-value products will be necessary: 'increased production will not necessarily mean greater use as an energy source, owing to the higher profitability of macroalgae in pharmaceutical, chemical and food markets' [67]. Likewise, 'Both algal forms may provide low value, high volume products such as livestock feeds, as well as high value, low volume speciality chemicals such as carotenoids and omega oils' [68].

A UK strategy report distinguishes between optimal pathways for micro and macro-algae (seaweed):

These were chosen based on a high-level assessment of deployment potential and because they have the potential to be grown in areas unsuitable for food crops, which is potentially more sustainable than first generation energy crops. Regarding conversion routes, microalgae is assessed as being used to produce transport fuels, and macroalgae (seaweed) is assessed as being used to produce biomethane in adapted anaerobic digestion systems [69].

Interest in algae has been shifting to macro-algae (seaweed), which can be mass-produced in temperate climates.

At a national level in terms of commodity-scale energy-type feedstocks, micro-algae is losing favour. Macro-algae

is emerging as something of interest, but it's far too early to say whether it's viable (interview, ETI, 08.0.12).

BP is a major global investor in biofuels R&D but has funded none in the UK. Judging that the best expertise was in the US, BP established the Energy Biosciences Institute in Berkeley. According to the Institute's report, fuel production from microalgae will be expensive, even with relatively favourable assumptions (e.g. low-cost system design, productivity algae cultivation, high oil content, low-cost harvesting and processing). Of various potential pathways, aviation fuel is especially promising [70]. According to the US Dept of Energy, micro-algae yield 30 times more energy per acre than land crops such as soy beans and can grow in seawater. Let us examine how analogous expectations gained credibility among UK arenas for funding algal bioenergy.

## 7.2. Carbon Trust programme funded and terminated

Since its establishment in 2001, the Carbon Trust has helped businesses to reduce GHG emissions by various means. It also runs 'technology acceleration' projects, aimed at identifying regulatory, financial and technical barriers to technology adoption, e.g. through trials and demonstration projects. It has had six main accelerators: biomass heat, low carbon buildings, industrial energy efficiency, micro combined heat and power, marine energy and offshore wind.

Within that framework, the government allocated £6 million to the Carbon Trust's Advanced Bioenergy Directed Research Accelerator [71]. This included an aim to develop algae as a biofuel source. Anticipating resource benefits, algal technology could avoid land-use issues by growing algae in seawater, wastewater or non-arable land. But algae remained distant from commercial feasibility, unlike the other accelerators.

In 2008 this initiative was expanded into the Algae Biofuels Challenge, a seven-year programme supported by DECC and the Department for Transport. It aimed to 'develop and prove leading UK algae biofuel technologies for export to other countries to help reduce global carbon emissions from aviation and road transport whilst generating significant UK economic benefit' [72]. As a key rationale for technology export, the northern European climate was not conducive for large-scale algae growth.

The programme aimed 'to commercialise the use of algae biofuel as an alternative to fossil-based oil by 2020', especially for aviation uses:

The major advantage of algae over other biofuel feedstocks, in particular feedstocks that provide oil for jet fuel and diesel, such as palm, is that it is more sustainable from both an environmental and socio-economic perspective.

As an early-stage technology, algae offered a special opportunity, even a 'multi-billion pound opportunity', according to Dr Mark Williamson, Innovations Director at the Carbon Trust. To fulfil that opportunity:

... we will be combining the UK's undoubted expertise in the area with our unique knowledge and experience of commercialising early stage low carbon technologies, to

give us the best possible chance of successfully producing cost-competitive algal biofuel at scale [73].

To choose the best research teams, the Carbon Trust recruited prominent scientists, many based in the USA; hence the 2008 programme launch was held in Seattle. So the programme was unilaterally funding transatlantic cooperation.

The idea was to bring together the best technology in the UK under the guidance of international experts. It was all going well. We did the landscaping and stakeholder engagement in 2008; the programme was launched later that year in Seattle. We started delivery at the beginning of 2010 (interview, Carbon Trust, 03.11.11).

The research was conducted by a 'dream team', comprising eleven UK institutions [74]. This team had the task to find a method for producing 70 billion litres of algae biofuel a year by 2030. This would be equivalent to 6% of global road transport diesel, saving over 160 million tonnes of CO<sub>2</sub> every year. The Carbon Trust planned to invest £8 million over three years into the programme [75].

The programme manager emphasised its credible model and expertise: 'We created a model that was very credible; it was recognised as being very credible. We elevated it to an international stage, we were so ahead of everyone else' (interview, Carbon Trust, 03.11.11).

Although not directly involving industry, the algae programme brought together expertise to anticipate questions that industry would ask and outcomes that would attract investors:

We hired the leading experts in the world. A lot of people don't like that because they find it anti-innovation. But this is what investors do. We used experts in techno-economics to look at where the cost breakthrough needed to come from and therefore where the innovation needed to come from. We did a carbon-life cycle analysis – the first of its kind in algae. We did a market-potential analysis to look at whether there is scalability to make it worthwhile. All technological programmes funded by our organisation go through the same process (interview, Carbon Trust, 03.11.11).

With a budget of £3–6 m, Phase One funded research, involving 74 scientists. Phase Two was expected to scale up and integrate the various processes developed in Phase One. But beforehand the entire programme was terminated by DECC in early 2011, less than a year after the start of the Conservative-Liberal Democrat coalition government.

Although reasons were not publicly stated, some were conveyed to the Carbon Trust: namely, because the algae programme was at 'the early stage of its technological development', and because 'the technology was not going to be deployed in the UK', as DECC told the programme manager [5]. The programme had originally gained credibility for expectations to commercialise 'early-stage technology' for export—a focus which soon became grounds for termination under a new government.

The programme died because of political decision rather than any rational basis. Research priorities change in

accordance with political landscapes. It is scary: algae is a good case study in the absurd way that public funding is managed (interview, Carbon Trust, 03.11.11).

As an extra potential reason, some observers questioned a slippage into hype:

Part of the rationale was to get some good, publicly available, shared data between several different groups on what really is possible and consider whether you ought to give more funding. In that way you can make a decent public well-informed decision. Unfortunately... everyone gets excited and thinks, 'We are doing this because algae is going to be great' – as opposed to 'We are doing this because we want to know whether algae is going to be great' (interview, E4tech, 03.08.12).

Doubts also arose about how to enforce patents. The Carbon Trust algae programme had originally emphasised the task to 'secure licenses to all intellectual property' [76]. It carefully planned arrangements to share and protect IP (interview, Carbon Trust, 03.11.11). But some experts questioned how a patent-holder could enforce such rights in Southern countries where the technology would be applied.

There are people who have had doubts about how you protect IP in some of these areas, but I think it is more geographical – protecting IP outside the UK.... People have less confidence about whether it [the product] is easily copy-able and whether you would end up leaking value (interview, E4tech, 03.08.12).

Another factor was a general policy move to eliminate or reduce many quangos, i.e. quasi-autonomous non-governmental organisations, dependent mainly on government funds. Around the same time as terminating the algae programme, DECC cut the Carbon Trust's 2011–12 budget by 40%. More generally, 'the Carbon Trust has been challenged by the growth of other policy initiatives in this area and is struggling to differentiate itself from and legitimise itself vis-à-vis these initiatives' [77]. Indeed, it was being marginalised through wider policy changes and budget cuts. Meanwhile funds were increased for scale-up projects through the Energy Technologies Institute, closely involving industry proposals and finance (see Section 4.2).

### 7.3. Public-private arrangements expand

Despite termination of the Algae Biofuels Challenge programme, there were new arenas for algal research. Hosted by the Biosciences Knowledge Transfer Network, the Algal Bioenergy Special Interest Group (AB-SIG) is a joint network between NERC and the Technology Strategy Board. The network provides a forum for circulating future expectations, evaluating prospects and presenting successful initiatives [78]. As a special opportunity for algae, 'If we can put an "environmental" tag on a product, then it can make more money; the future is very bright and the possibilities are endless', declared the AB-SIG Chair.

Speaking to an international conference, she elaborated the possibilities:

Extraction of high-value components of algae (e.g. carotenoids, anti-oxidants) could help underpin the economic viability of algae-based biorefineries. By-products could be used as a protein-enriched source of animal feed or to capture energy within the system e.g. through anaerobic digestion for CH<sub>4</sub> production [79].

At the AB-SIG's own 2012 conference, speakers emphasised that biomass sustainability and productivity remain a major problem, even for second-generation biofuels. Large-scale low-value fuel production may not become commercially viable, so higher-value products may be necessary. Algae could provide a solution, according to an expert study [80].

As a shared view, R&D priorities should relate closely to industry needs: 'Finding out what the clients really want from algal bioenergy is challenging. One needs to find out what they want; otherwise one is wasting time' (speaker at AB-SIG conference, 20.06.12). As another caveat, some patents may not be defensible in legal procedures. Much current research had already been done, even with results published. Researchers have not carried out an adequate literature survey since the 1980s, so they unwittingly repeat previous research.

Most algae research is re-inventing the wheel. Many researchers have not done a literature search. So their patents could be challenged on grounds that the knowledge is not an inventive step [5].

To address various doubts and obstacles, public-sector researchers have developed several strategies, e.g. better-targeted biofuels, higher-value products, rigorously novel approaches, closer links with industry, etc. From such strategies, public-sector bodies have gained funds or created partnerships with companies, some based abroad. Those efforts can be illustrated by several projects.

Cranfield University has focused on aviation fuel with funds from the airline industry. Called 4th generation biofuel, this initiative seeks to enhance algae production as feedstock:

Algae can be an eco-friendly substitute for fossil fuel or synthetic chemicals.... Each generation of biofuels will be greener than the previous one.... Market drivers of aviation biofuel include: fuel security, macro-economics, niche markets de-risking new technology in scale-up... Aviation-biofuel from algae may seem like sci-fi now, but it's not a million miles away [81].

The Cranfield project foresees special opportunities for aviation fuel from algae:

There are two reasons for a special connection. The aviation industry seeks a reliable, abundant biomass source which will not compete with other uses or with land use. And seawater micro-algae can produce oils which are specially



suitable for aviation fuel. All the elements of the process already exist, but they need a better engineering design for viable large-scale production (interview, Cranfield, 20.06.12).

A public-sector institute, Nottingham Microalgae Biorefinery, has designed a process for various 'green' products sought by industry. This initiative has been designed for low-volume high-value products. As an incentive for private investment, companies seek to replace petrochemical sources with bio-materials for their pharmaceutical products. For the production facility, the efficient photo bioreactor (PBR) has proprietary technology which can be licensed more widely; benefits are to be negotiated among the industrial partners. Boots has a Combined Heat and Power (CHP) facility at their UK production site in the UK; the PBR will be sited adjacent to the CHP plant to take advantage of synergies, e.g. enabling CHP flue-gas to be pumped to the PBR to supplement algae growth through enriched CO<sub>2</sub> [82]. The researchers expect to valorise the IP, partly thanks to their prior literature search:

The first protection issue for IP is a claim that the basic knowledge already existed. I chose our research angle because it is truly novel; this also may help protect it from being copied (interview, 20.06.12, Nottingham Microalgae Biorefinery).

A macroalgae route to a 'green' image is illustrated by an Irish company developing substitutes for chemical-based additives in aquaculture and animal feed. Impetus comes partly from more stringent European regulation of antibiotics. Based on seaweed, 'Ocean Harvest' nutrients have already gone into large-scale commercial production. Tests have indicated GHG savings in the production process and improvements in animal health [83].

A public-sector institute, Scottish Bioenergy, has been exploring similar routes through macroalgae, while also broadening its original aims to encompass higher-value products such as 'natural' feed for animals and fish. Algae-to-biogas pathways have a symbiosis with anaerobic digestion, whose wastewater in turn can be used as a fertiliser. In exploring these diverse algal pathways, 'Scottish Bioenergy has become less Scottish', i.e. more dependent on international investors [84].

A similar globalisation tendency has arisen in several UK public-sector initiatives for algal products. They have sought partners abroad, e.g. the oil company Repsol [85]. In such ways, competitiveness means that UK initiatives compete against each other—by contrast with policy discourse about UK R&D promoting a national economic advantage and growth.

## 8. Conclusions: arenas of expectations

The UK government has promoted bioenergy for several policy aims—to decarbonise the economy in cost-effective ways, as well as to gain national benefits such as a competitive advantage, technology export, energy security and waste management. Through claims or promises to provide such benefits, bioenergy promoters have sought state funds for various innovation pathways. For some pathways (such as advanced biofuels and gasification),

expert reports have acknowledged greater technical difficulties, implying longer timescales and larger investment necessary before commercial viability—often as grounds to allocate considerable state investment. How do some innovation pathways become priorities for state funds?

Some pathways have been favoured by specific state-industry arrangements, which serve as 'arenas of expectations'. Collective expectations have been shaped by close exchanges between state bodies, industry and expert consultancies. Industry has informed expert reports on research needs, technical prospects and future benefits, in ways conflating public and private interests, especially the aim to maintain and justify current infrastructure as 'low-carbon'. Links between arenas, more credible expectations and innovation priorities are summarised in Table 1, as recapitulated in the following paragraphs.

Funding 'strategic research', research councils have justified their bioenergy priorities in terms of national needs and policy aims. Scientists have proposed R&D agendas as means to fulfil those aims and to attract industry co-financing, which has been an advantage in competing for grant proposals. Such arrangements have resulted in weak support for hydrogen fuel cells, while directing funds towards advanced biofuels around several expectations—as an environmentally sustainable means to fulfil mandatory targets by 2020, as an innovation complementing companies' past investment in vehicle-energy infrastructure, and as a step towards higher-value products.

Collective expectations for future biofuels illustrate how 'next-generation' technologies can become self-justifying [86]. For advanced biofuels, extra economic benefits are foreseen from UK technoscientific strengths entering global partnerships which gain intellectual property. The global character of such linkages has been explicit. This contrasts with UK research policy in general, which has justified R&D as a direct means to national economic growth [87].

For commercial scale-up, novel pathways need capital investment, with great uncertainty about necessary costs and timescales for technical success. The Bioenergy Capital Grants Scheme funded a wide range of pathways, but this support was inadequate, especially for less-ready technologies. DECC had an unclear basis for judgements about which pathways should still gain funds. Given such difficulties, the scheme is being abandoned.

ETI was established with a club structure, whereby large companies jointly choose and fund expensive scale-up projects, expecting multiple economic benefits. Here the same actor has played the roles of technology enactor and selector, thus blurring their boundary in priority-setting processes (see Section 2.2, diagram). Two examples: Despite earlier technical failures, gasification gained greater funds through expectations for technology export and cheaper waste management. For bioenergy-CCS, expectations for GHG savings help to maintain current carbon-intensive infrastructure such as the internal combustion engine and coal-fired electricity-only plants.

The Carbon Trust programme emphasised national technoscientific expertise around algal biofuels, while also anticipating UK industry's future needs but with no direct involvement. This large programme was prematurely abandoned by the government, apparently for several reasons, especially a new government shifting the criteria for expectations. Despite the programme's termination, UK public-sector institutes have gained company investment for other algal



projects, especially aiming at aviation fuel and higher-value products. Project managers emphasise strategies to optimise market value and defend intellectual property, thus addressing earlier doubts and so enhancing credibility. Thus algal bioenergy illustrates a lower-level differentiation of arenas and pathways.

In sum: Through various state-industry arrangements, some expectations have been made more credible, thus justifying and prioritising resource allocation. Conversely, to incentivise private-sector investment, government has sought credibility for its commitment to bioenergy innovation and future markets. These dual efforts illustrate the reciprocal character of promise-requirement cycles, whereby promises are turned into requirements for state sponsors as well as for innovators.

The credibility of expectations has been linked with UK economic and environmental aims. Interdependent expectations have made overall credibility dependent on multiple pathways, while also shifting expectations to bypass obstacles. When encountering technical difficulties or delays, pathways and their expectations have been broadened, e.g. to waste management or higher-value products, especially through new arenas. Thus the concept 'arenas of expectations' helps to explain how some pathways gain favour as innovation priorities. Hype cycles have undergone shifts in expectations, arenas and priorities being favoured there.

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